Static and dynamic soil characterization at Roio Piano (AQ)

Piera Paola Capilleri,* Antonio Cavallaro,** Michele Maugeri***

Summary

Following the 6 April 2009 earthquake which hit the Abruzzo region, numerous static and dynamic field soil characterizations have been performed, in order to analyze the seismic response of soils (Grasso *et al*. 2005, Lanzo *et al*., 2011, Maugeri *et al*., 2011) and recover or retrofit buildings and important historical monuments. Among the numerous on-site investigations which took place in different parts of L'Aquila province, this paper reports the site investigations at Roio Piano. In particular, the results from in situ Seismic Dilatometer Marchetti Tests (SDMT) and soil laboratory tests are reported.

As regards dynamic laboratory tests, the resonant column test was used to evaluate the soil geotechnical parameters in terms of the shear modulus G-γ and damping ratio D-γ.

Keywords: earthquake, SDMT, shear modulus, soil damping.

1. Introduction

On Monday April 6th, 2009 a strong earthquake (M_L = 5.8 and M_W = 6.3) struck the city of L'Aquila in central Italy and the surrounding villages. The earthquake caused severe damage to about 18000 buildings [Akinci *et al.,* 2010], in the medieval city of L'Aquila. Several buildings collapsed, 308 people were killed, 1600 people were injured, while around 40000 people were made homeless. Many modern buildings suffered great damage, for example the dormitory at the University of L'Aquila collapsed, causing 15 deaths and the new hospital, inaugurated in 2000, was damaged and has since remained closed. As regards site effects, ground failure, failure in hard rock slopes, sinkholes and soil liquefaction phenomenon occurred [Monaco *et al.,* 2012]. One particular liquefaction phenomenon occurred at Vittorito, 40 km from the epicentre, as reported by Monaco *et al.* [2011].

The emergency scenario imposed very strict time constraints for decisions on reconstruction. Only a few weeks after the mainshock, the Civil Defence Department identified about 20 sites where the first temporary houses for homeless people could be located. These buildings (C.A.S.E. Project) were conceived to be seismically isolated, so one of the requirements to be satisfied in assessing the location was that the natural frequency of the subsoil should not be lower than 0.5 Hz. In situ and laboratory tests were carried out to obtain an accurate quick dynamic subsoil characterization of these sites; in situ CPT and SDMT tests were performed, as well as boreholes, D-H tests and surface wave MASW tests.

Similar geotechnical study was successful performed for significant historical test sites [Cavallaro *et al.,* 1999a, 1999b, 2003, 2004, 2012, 2013a; Lo Presti *et al.,* 1999a].

Finally a task force from the Italian Geotechnical Society (AGI) performed laboratory tests to achieve a static and dynamic characterization. The results of the SDMT and laboratory tests performed at Roio Piano are reported in this paper.

2. Seismicity of area

The L'Aquila area had experienced several large historical earthquakes, so that the latest event was not unexpected. According to historical records the town suffered shaking at intensities of MCS IX or higher, with catastrophic earthquakes occurring in 1349, 1461 and 1703 [INGV- Database Macrosismico Italiano, 2004; Tertulliani *et al.,* 2009], [Blumetti, 1995]. So, in the light of the historical earthquake records, the L'Aquila area had already been identified as having a relatively high seismic hazard [Slejko *et al.,* 1998; GNDT-SSN, 2001; Rebez *et al.,* 2001]; in accordance with the N.T.C. [2008] building codes, the peak horizontal ground acceleration at the rock surface has been evaluated: a_g = 0.225-0.25g, with a probability of exceedance of less than 10 % in 50 years. Moreover, during the 2009 event the maximum recorded acceleration was a_g = 0.65g at the AQV sta-

* Ph.D. Geotechnical Engineering, Department of Civil and Environmental Engineering, University of Catania, Catania (Italy)

** Senior Researcher, CNR-IBAM, Catania, Italy

*** Full Professor of Geotechnical Engineering, Department of Civil and Environmental Engineering, University of Catania, Catania (Italy)

tion in the middle of the Aterno River. At the AQK station located in the middle of L'Aquila city the maximum horizontal peak acceleration recorded was 0.35g while the normal one was 0.37g, higher than the horizontal one, because of the normal fault mechanism.

3. Geological background

The city of L'Aquila and most of the small towns damaged by the April 6th, 2009 earthquake lie in a vast intra-Apennine tectonic basin, elongated in a NW-SE direction, parallel to active normal faults, and surrounded by the high peaks of the Gran Sasso and the Velino-Sirente mountains.

The Aterno River is the main hydrographic element of the basin; the middle Aterno river valley is about 10 km wide and is elongated in the NW-SE direction for more than 15 km. The current geological setting of the L'Aquila basin results from a complex sequence of depositional events, due to erosion and tectonics.

The geological setting of the L'Aquila basin is illustrated in the geological map and the schematic section in figure 1. The bedrock consists of Meso-Cenozoic limestone formations, generally outcropping along the sides of the valley and on ridges located within the Aterno River basin.

The bottom of the valley was filled during the Quaternary period with continental deposits of variable genesis and deposition age, resulting from lacustrine to subsequent fluvial sedimentations. The maximum thickness of the Quaternary deposits is estimated as being about 400-500 m high.

The older Pleistocene lacustrine deposits, placed on the calcareous bedrock, form a complex depositional sequence of silt, sand and conglomerate units [BOSI and BERTINI, 1970; BERTINI *et al.,* 1989]. In detail, three different units may be distinguished within the lacustrine formation:

– an older unit at the bottom (placed over the bedrock) of highly variable composition, mostly different combinations of gravels, sands and clays;
– an intermediate unit, predominantly consisting of gravels and sands;

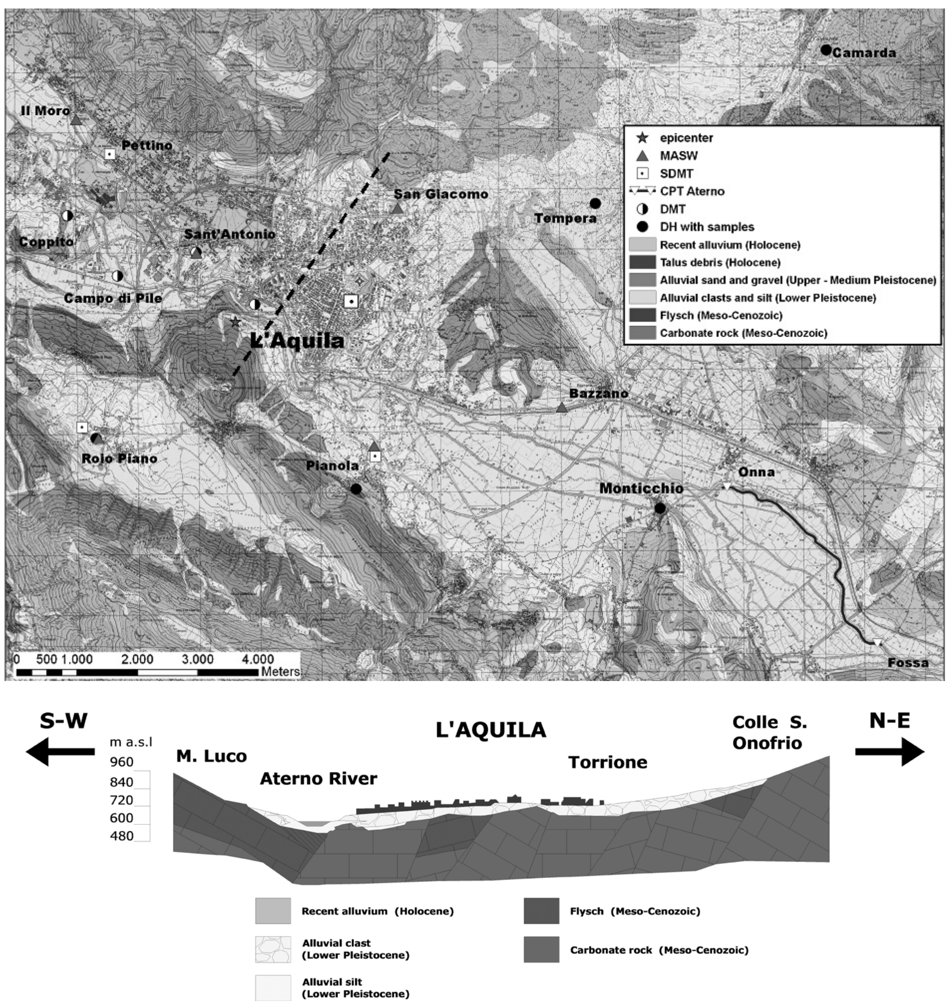


Fig. 1 – Geological map of the L'Aquila area and schematic section across the town centre of L'Aquila (modified after APAT, 2006).
Fig. 1 – Mappa geologica della zona di L'Aquila e sezione del centro della città di L'Aquila (modificata da APAT, 2006).

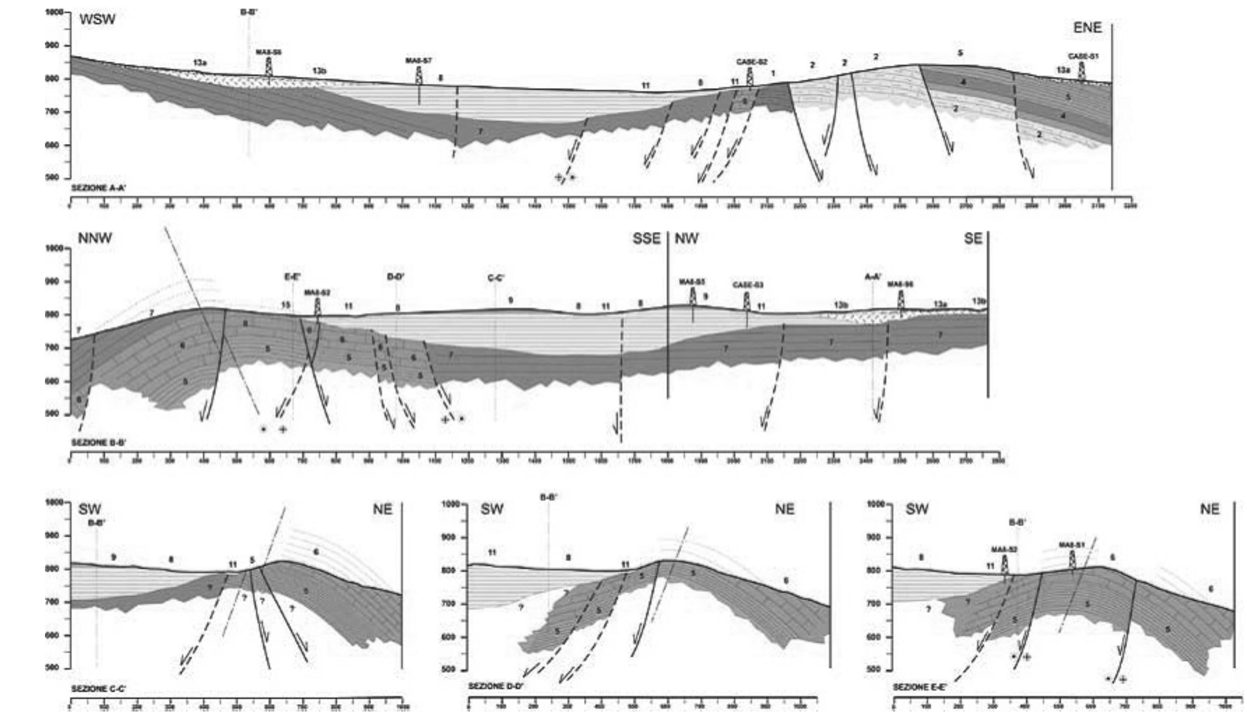


Fig. 2 – Geological cross-section of the Roio Piano area (Gruppo di lavoro MS- AQ, 2010).
Fig. 2 – Sezione geologica dell'area di Roio Piano (Gruppo di lavoro MS- AQ, 2010).

– a more recent unit at the top, mainly consisting of sands and clays, having a thickness of some tens of meters.

The area on the left side of the Aterno River basin, where the old town centre of L'Aquila is located, is characterized by the presence of vast deposits of Pleistocene heterometric breccias (associated with Quaternary paleolandslides), known as "Megabreccias", overlying the lacustrine sequence placed on the bedrock. The "Megabreccias" consist of limestone boulders and alluvial clasts varying in size from a few centimeters to some meters, embedded in a sandy-silty matrix having a highly variable degree of cementation [BOSI and BERTINI, 1970; BERTINI *et al.*, 1989].

In particular, the lithofacies outcrops in the Roio Piano area include slope-basin deposits of Cretaceous and Paleogene-Miocene ramp (deposits).

The oldest term outcropping in the study area is represented by Scaglia debris. In this unit the terms correspond to the typical contemporary formations of red and white Scaglia formation in the Umbria-Marche succession, from which they differ mainly due to the large quantity of biodetritus. The content is prevalently bioclastic from rudist fragments which are associated with coral, echinoderm and brachiopod fragments. As regards the Scaglia debris there were two distinct facies associations (Gruppo di lavoro MS- AQ 2010).

Based on the spatial distribution of the main systems of normal faults it is possible to define the Roio basin as a semi-Graben, bounded by the Appenine fault systems to the EW, while the western sector does not present evidence of extensional systems (Fig. 2).

Aftershock recordings were made by the INGV located immediately south of the red zone.

At Roio Piano (Fig. 3) two borings were carried out, equipped for down-hole tests and SPT. ReMi geophysical tests were carried out in six locations in the town and environmental noise HVSR tests were performed at 18 sites. Finally, the string for the MASW tests was placed to the SE of the village.

4. Geotechnical characterization by SDMT test

A few weeks after the main shock, the Civil Protection Department (DPC) identified about 20 sites to locate the first temporary houses for the homeless (Fig. 4).

The Roio Piano (AQ) area measuring 212400 sq.m, located to the south of the city of L'Aquila, was investigated up to a maximum depth of 70 m. Borehole and Down-Hole (DH) tests were performed up to 50 m, SMDT tests up to 20 m and MASW up to 70 m.

The borehole shows at the top a layer of clayey silty soil with brown sand with a shallow vegetable component, of thickness ranging from 0 to about 2 m. Then, five slightly different units can be recognized: a layer of yellow sandy silt with millimeters calcareous sandy clasts levels with thickness ranging from about 2 m to 8.3 m; a layer of sandy silt with grey sand with thickness ranging from 8.30 m to 12 m; a formation of alternation of clear grey clayey silt and redly yellow

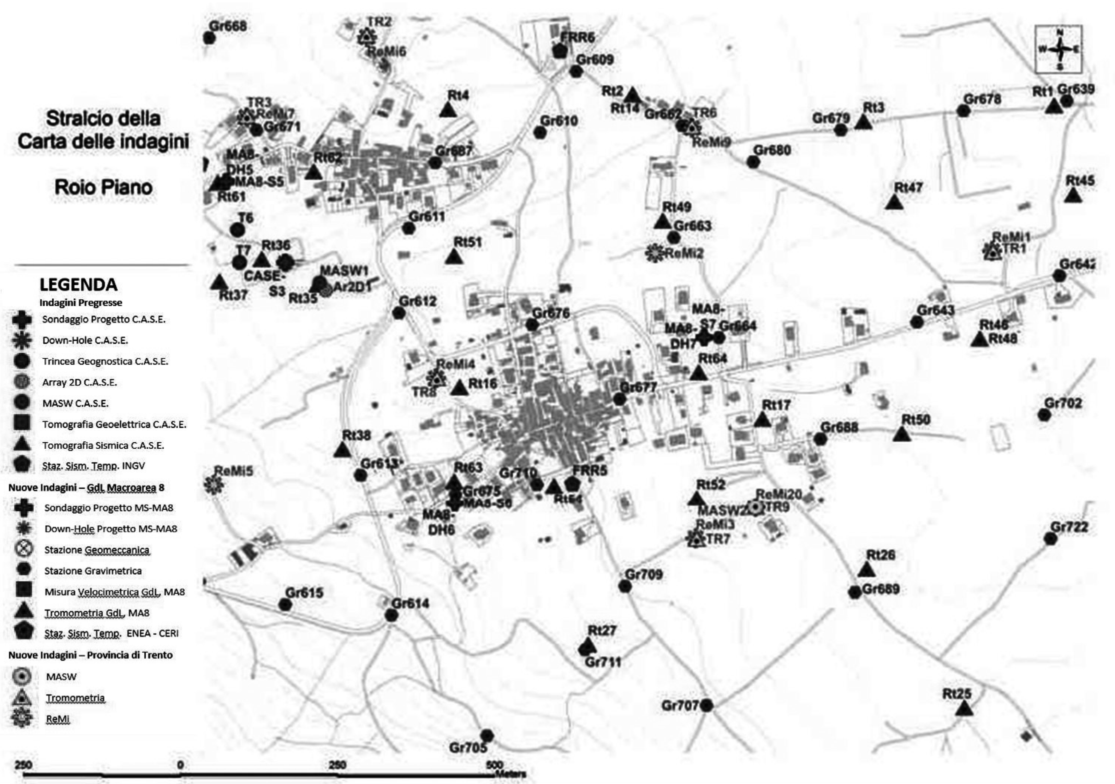


Fig. 3 – Detail of the maps related to the Roio Piano investigation (Gruppo di lavoro MS- AQ, 2010).
Fig. 3 – Particolare della carte delle indagini relativa a Roio Piano (Gruppo di lavoro MS- AQ, 2010).

sand with thickness ranging from 12 m to about 14.80 m; a layer of uniform grey clayey silt with centimeters sandy level of high stiff with thickness ranging from 14.80 m to about 35.00 m; finally a layer of marly level inside grey clayey silty soil with thickness ranging from 35.00 m until to the end of borehole. The natural water level is of about 5.00 m below the ground level.

Static and dynamic soil characterizations were required for each site. For an accurate, yet quick, dynamic subsoil characterization of these sites, surface wave tests (MASW) were planned for all of them; Down-Hole and laboratory tests were performed only where the top of the seismic bedrock appeared shallow. The Italian Geotechnical Society (AGI) task force was employed to investigate several of these sites using surface wave, seismic dilatometer tests and laboratory tests.

There follows a report on the seismic dilatometer test results, then the test results are compared with the results obtained from the down-hole and surface wave tests (MASW).

Figure 4 – Location of the 20 temporary housing sites indentified by the DPC (C.A.S.E. Project).
Figure 4 – Ubicazione dei 20 siti provvisori individuati dal DPC (Progetto C.A.S.E.).

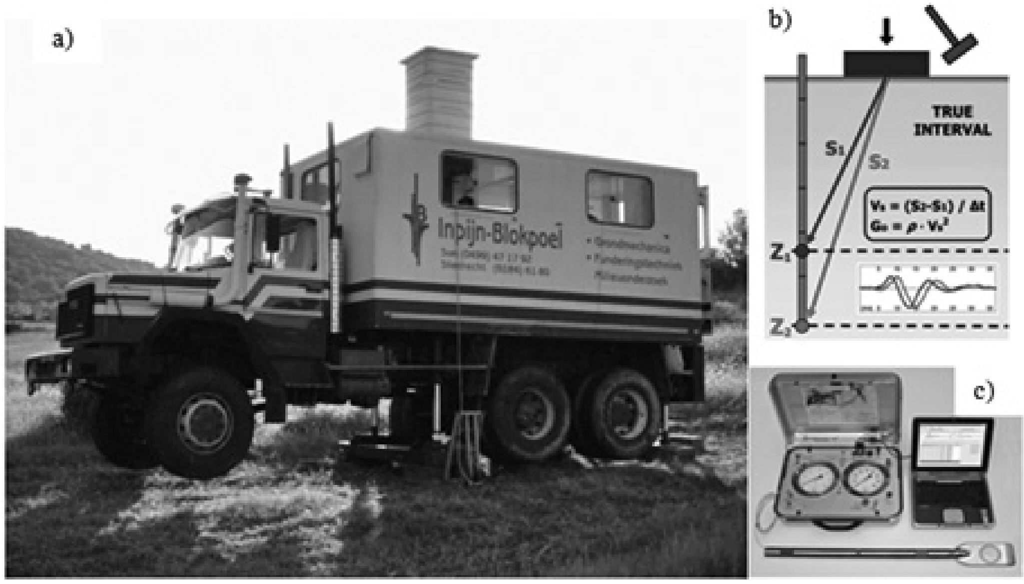


Fig. 5 – SDMT tests : a) view of the SDMT equipment; b) the scheme of SDMT tests; c) the blade with the sensor for V_s measurement and the registration system.

Fig. 5 – Prova SDMT: a) vista dell'attrezzatura SDMT; b) schema della prova SDMT; c) lama con i due sensori per la misura delle V_S e il sistema di registrazione.

The small strain ($\gamma \leq 0.001$ %) shear modulus, G_o, was determined from DMT tests. The Marchetti Seismic Dilatometer (SDMT) is an instrument resulting from combining the DMT blade [MARCHETTI, 1980] with a seismic modulus measuring the shear wave velocity V_S.

A new SDMT system (Fig. 5) has been recently developed in Italy as was reported by MARCHETTI *et al.*, (2008). This apparatus was also used in offshore condition by CAVALLARO *et al.* [2013b; 2013c].

The seismic modulus is a cylindrical instrumented tube, located above the DMT blade (see Fig. 5c), housing two receivers at a distance of 0.50 m. The test configuration "two receivers"/"true interval" avoids problems connected with the possible inaccurate determination of the "first arrival" time sometimes met with the "pseudo interval" configuration (just one receiver). Also the pair of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow and not to different blows in sequence, which are not necessarily identical. The adoption of the "true interval" configuration considerably enhances the repeatability of the V_S measurement (observed repeatability $V_S \approx 1 - 2$ %).

V_S is obtained (Fig. 5b) as the ratio between the difference in distance of the two receivers (50 cm) and the delay in the arrival of the impulse from the first to the second receiver (Δt). The shear wave source at the surface is generated by a pendulum hammer ($\approx$ 10 kg) which hits horizontally a steel rectangular base pressed vertically against the soil (by the weight of the truck, see Fig. 5a) and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the shear wave generated.

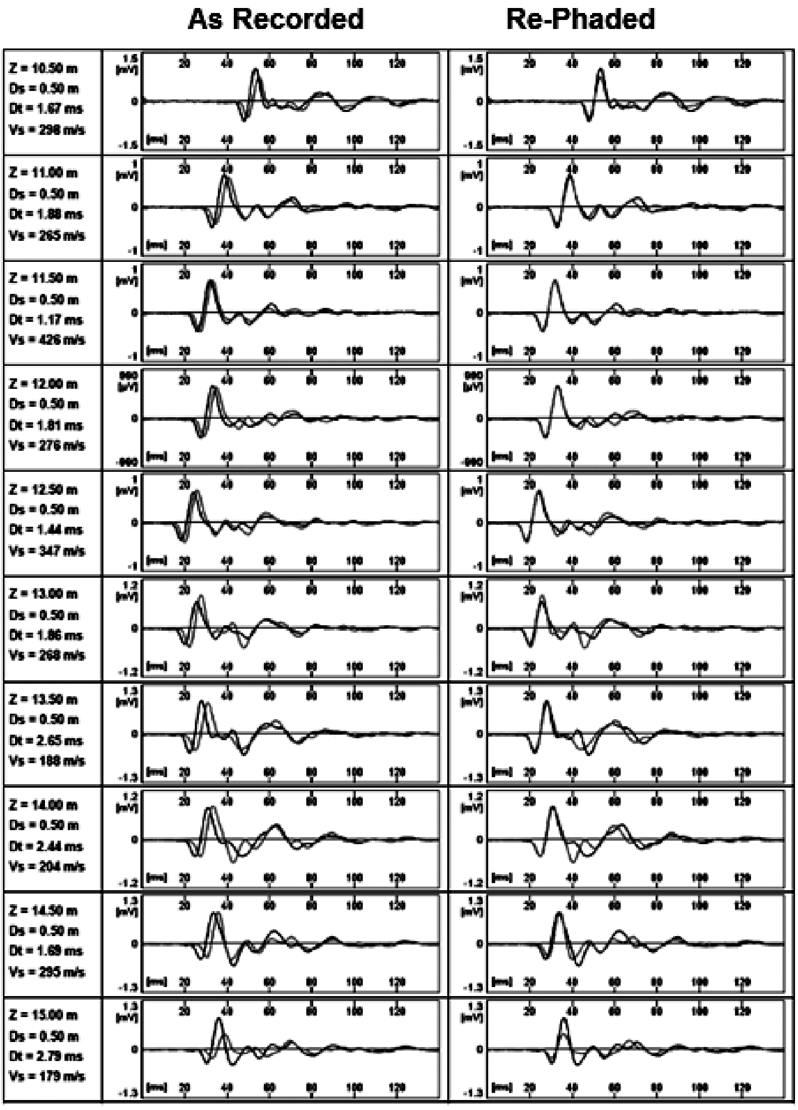
Determining the delay from SDMT seismograms, normally carried out using a cross-correlation algorithm, is generally well conditioned, given that it is based on two seismograms (Fig. 6). This is particularly so for the initial waves, which are not based only on the first arrival time or specific marker points in the seismogram.

Figure 6 shows an example of seismograms obtained by SDMT at various test depths at the Roio Piano site. It is a good practice to plot the seismograms side-by-side as they are recorded and re-phased according to the calculated delay. Figure 6a shows the registered waves at the first receivers, the registered waves at the second receivers and the rephrase waves to evaluate the shear waves velocity. Figure 6b shows the repeatability of the shear waves measurements with an average variation coefficient of about 1.0 %.

Figure 7 shows an example of the typical results obtained by the SDMT. These include the V_S profile as well as the profiles for four basic DMT parameters: the material index I_d, that gives information on soil type (sand, silt, clay); the drained constrained Modulus M; the undrained shear strength c_u and the horizontal stress index K_d (related to OCR), obtained using current DMT correlations.

The K_d profile is similar in shape to the profile of the over-consolidation ratio OCR. $K_d = 2$ indicates in clays OCR = 1, $K_d > 2$ indicates over-consolidation.

Finally, in figure 8 a comparison of results obtained from the SDMT, DH and MASW tests shows a good agreement between them [MONACO *et al.*, 2012].



a)

Z [m]	Vs [m/s]	Ripetibilità Vs [m/s]	Coeff. Var [%]
0.50	43	43,43,43	0.00
1.00	241	244,245,235	1.87
1.50	212	213,212	0.33
2.00	208	209,208	0.34
2.50	226	226,225	0.31
3.00	234	234,235	0.30
3.50	262	262,263	0.27
4.00	262	262,261	0.27
4.50	284	285,282	0.56
5.00	236	237,234	0.67
5.50	226	226,226	0.00
6.00	221	222,220	0.45
6.50	223	223,223	0.00
7.00	285	286,284,285	0.29
7.50	256	257,254	0.62
8.00	308	306,309	0.51
8.50	387	398,376	2.84
9.00	372	372,371	0.19
9.50	223	230,216	3.14
10.00	424	439,410	3.42
10.50	297	298,296	0.34
11.00	252	251,252	0.28
11.50	418	417,420	0.38
12.00	283	283,283	0.00
12.50	312	312,313	0.23
13.00	269	268,270	0.37
13.50	186	186,186	0.00
14.00	204	204,205	0.35
14.50	334	334,334	0.00
15.00	172	173,172	0.41
15.50	353	355,351	0.57
16.00	362	359,366	0.98
16.50	256	256,255	0.28
17.00	301	317,285	5.32
17.50	326	331,321	1.53
18.00	224	222,226	0.89
18.50	246	249,244	1.04
19.00	356	353,358	0.72
19.50	404	401,407	0.74
20.00	124	122,127	2.06
20.50	632	633,631	0.16
21.00	200	203,197	1.50
21.50	266	267,265	0.38
22.00	259	256,261	0.99
22.40	234	234,235	0.30

b)

Fig. 6 – Example of seismograms obtained by SDMT: a) Registered waves at the first receivers registered waves at the second receivers and the rephrased waves at depths from 10.50 to 15.00 m; b) repeatability of the shear wave measurements with the variation coefficient for the all the test depths.

Fig. 6 – Esempio di sismogramma ottenuto da prova SDMT: a) Onde registrate dal primo ricevitore, onde registrate dal secondo ricevitore e onde rifasate alla profondità da 10,50 – 15.00 m; b) ripetibilità della misura delle onde di taglio con il coefficiente di variazione per tutte le profondità della prova.

5. Geotechnical characterization by laboratory test in the static field

Seven undisturbed samples were retrieved by means of Shelby tube sampling and tested by a network of soil laboratories at the Universities of Catania, Florence, Naples, Rome (La Sapienza) and Turin Polytechnic that were involved in performing the laboratory tests. The S3C1 and S3C5 samples (Tab. I), retrieved from borehole 3, were tested at the University of Catania. Borehole 3 shows alternating layers of clay silt and silt clay up to a depth of 35 m. Sample C1 was taken at a depth of 4.00-4.50 m in a yellow silt-sand layer while sample C5 was taken at a depth of 18.00-18.50 m in a grey silt-clay layer. The water table was found at a depth of 5 m in borehole 3.

The results obtained show that the soil at Roio Piano (AQ), is characterised by a clay soil, with a predominant clay fraction (CF) in the range of 19 – 48 %. This percentage decreases to 5 % at a depth of 12 m where a silty fraction of 79 % is observed. The gravel fraction remains zero. The sand fraction is in the range of about 0 – 20 %. The values of the natural moisture content, w_n, ranges from between 22 and 54 %. Characteristic values for the Atterberg limits are:

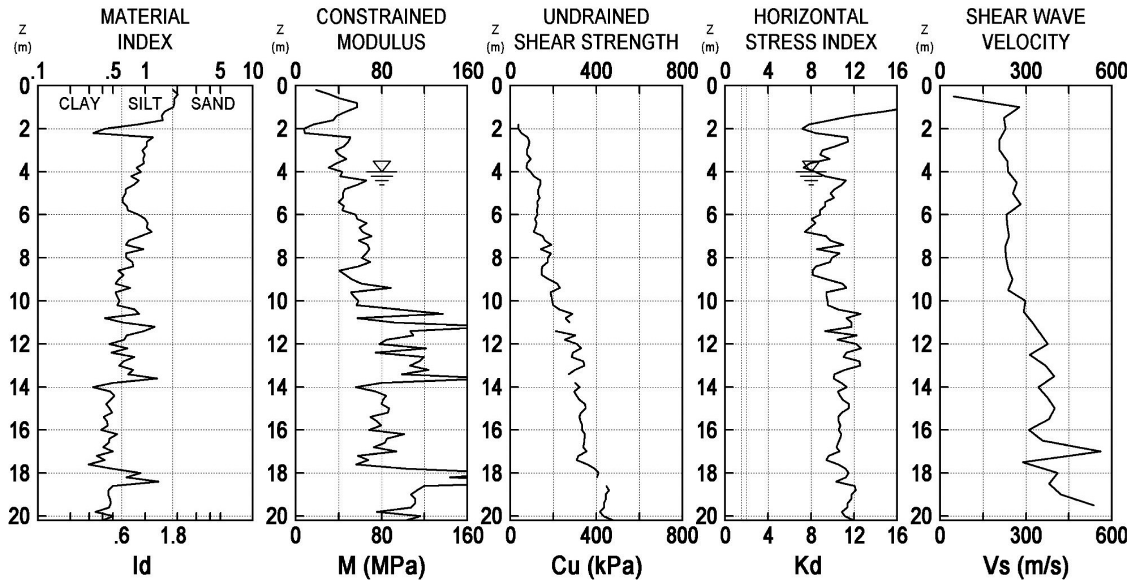


Fig. 7 – SDMT profiles for the Roio Piano site.
Fig. 7 – Profili SDMT per il sito di Roio Piano.

w_L = 34 % and w_p = 18 – 23 %, with a plasticity index of PI = 11 – 32 %.

Figure 9 shows the particle size distribution of the tested soils for Roio Piano. The typical range of physical characteristics, index properties and strength parameters for the deposit are reported in table I. As regards strength parameters, on the basis of the SDMT results, the C_u is 180 kPa up to a depth of seven metres and then increases linearly with depth.

A direct shear test at slow strain rate (0.019 mm/min) was performed to evaluate the drained shear strain. The result obtained shows c'= 20 kPa and ϕ'= 29°

The oedometer test results show E_{ed} values of 17.8 and 52.3 Mpa respectively for samples S3C1 and S3C5. These values are less than those which could be to derive from dilatometer modulus M (Fig. 7) by empirical correlation. That could be due to the sample disturbance during sampling.

The pre-consolidation pressure σ'_p and the overconsolidation ratio OCR = σ'_p/σ'_{vo} were evaluated from the 24h compression curves of 5 incremental loading (IL) oedometer tests (Fig. 10). Moreover, a SDMT was used to assess OCR and the coefficient of earth pressure at rest K_o following the procedure suggested by MARCHETTI [1980].

The comparison of results obtained from laboratory and in situ tests is summarized in figure 11. The OCR values obtained from the SDMT ran-

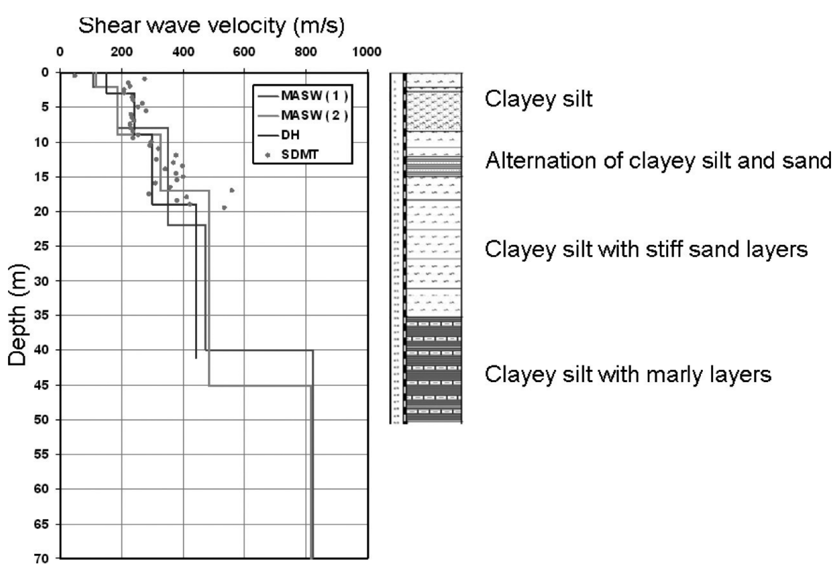


Fig. 8 – Shear wave velocity profiles obtained at Roio Piano by SDMT, DH and MASW tests (from MONACO *et al.*, 2012).
Fig. 8 – Profili delle velocità delle onde di taglio ottenute a Roio Piano da prove SDMT, DH e MASW (da MONACO et al.*, 2012).*

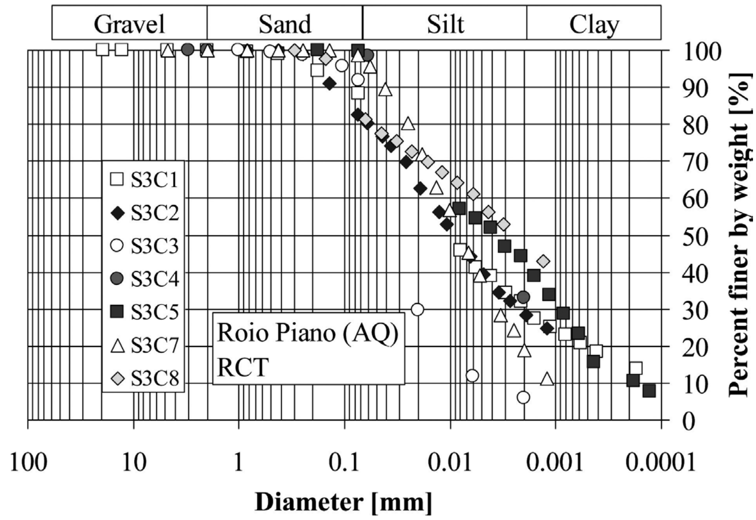


Fig. 9 – Particle size distribution of the tested soils for Roio Piano (C.A.S.E. Project).
Fig. 9 – Distribuzione delle dimensioni delle particelle dei terreni analizzati per il paese di Roio Piano (Progetto C.A.S.E.).

ge from 7 to 18 with an average value of about 13-15, showing that the soil is significantly over-consolidated probably also due to cementation. The soil overconsolidation is confirmed by the earth pressure at rest K_o which ranges from 1.5 to 2.

It should also be mentioned that the OCR values inferred from oedometer tests are lower than those obtained from in situ tests. One possible explanation of these differences could be that lower values of the preconsolidation pressure σ'_p are obtained in the laboratory because of cemented and disturbed samples.

6. Geotechnical characterization by laboratory tests in the dynamic field

To evaluate the soil dynamic properties so as to perform a site response analysis the shear modulus G and the damping ratio D of Roio Piano deposits were obtained in the laboratory by Resonant Column tests (RCT). All tests were performed on the Shelby tube C1specimens retrieved from the S3 boring. The sample was initially consolidated at the mean in situ effective stress and then, after the tests, was reconsolidated at increasing confining pressure values [Cavallaro *et al.,* 2005; 2006; 2007].

G is the unload-reload shear modulus evaluated from RCT, while G_o is the maximum value or "plateau" value as observed in the G-log(γ) plot. Generally G is constant until a certain strain limit is exceeded.

The small strain shear modulus G_o and damping ratio D obtained by RCT using different values of confining pressure are listed in table II.

The same specimen was subjected to RCT tests with different steps of consolidation stress, after a rest period of 24 hrs with open drainage. The size of the solid cylindrical specimens were Radius = 25 mm and Height = 100 mm.

Tab. I – Physical characteristics of Roio Piano (AQ) soil samples.
Tab. I – Caratteristiche fisiche dei campioni di Roio Piano.

Sample	Depth (m)	γ (kN/m^3)	e	w (%)	PI (%)	O.C.R.	Sand (%)	Silt (%)	Clay (%)	Laboratory
S3 C1	4.00-4.50	20.06	0,640	22.20	16.03	4.89	18	51	31	Catania
S3 C2	7.00-7.50	20.00	0,630	21.70	19.00	-	20	51	29	Rome
S3 C3	12.00-12.50	19.78	0,662	25.70	15.00	-	16	79	5	Florence
S3 C4	15.00-15.40	17.50	0,684	10.50	16.90	-	1	66	33	Turin
S3 C5	18.00-18.50	20.12	0,660	25.55	10.80	1.18	5	52	43	Catania
S3 C7	33.00-33.40	20.59	0,606	22.40	14.00	-	-	81	19	Rome
S3 C8	49.60-50.00	15.68	1,440	54.00	32.90	-	20	28	48	Naples

DSDSS: Double Specimen Direct Simple Shear Test; TS: Torsional Shear Tests; RC: Resonant Column Test.

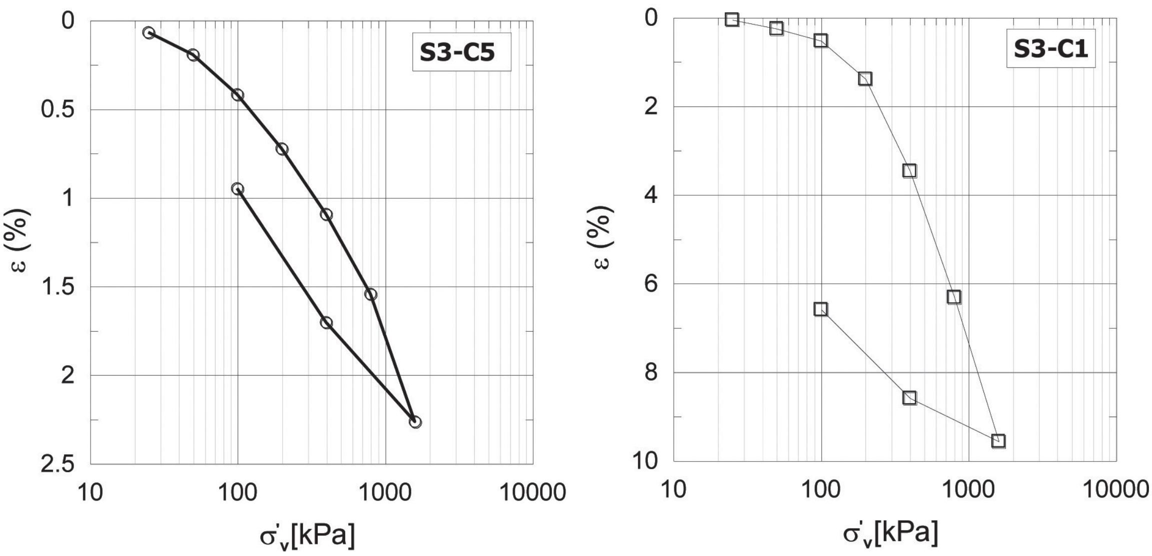


Fig. 10 – Oedometer curve for Roio Piano samples.
Fig. 10 – Curve edometriche per i campioni di Roio Piano.

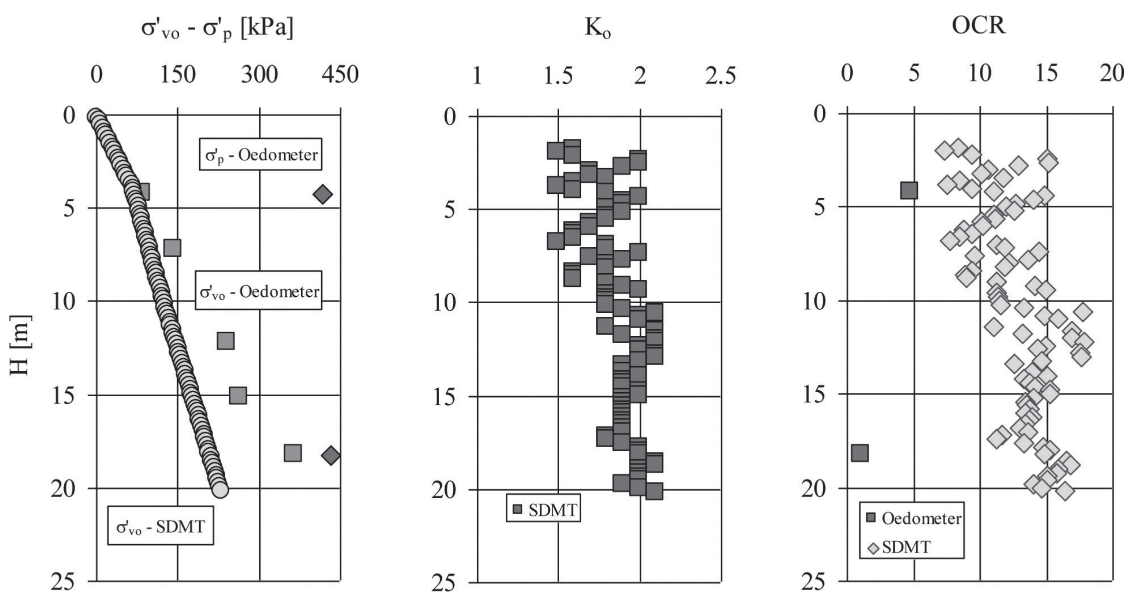


Fig. 11 – Profile of stress history from in situ and laboratory tests.
Fig. 11 – Profilo delle storie tensionali da prove in situ e di laboratorio.

The tests results are shown in figure 12. The G_o values, reported in table II, indicate a significant influence of consolidation stress level at very small strain, where the soil behaviour is supposed to be elastic. This effect became less evident with the shear strain increases, where the degradation phenomena occurs [LO PRESTI *et al.*, 1999b].

Figure 13 shows the results of RCT tests normalised by dividing the shear modulus $G(\gamma)$ by the initial value G_o at very low strain.

An interpretation of the experimental results for specimens from the Roio Piano site was made using the equation proposed by YOKOTA *et al.* [1981]; the empirical parameters to describe the shear modulus

Tab. II – Test Conditions for Roio Piano Area Specimens.
Tab. II – Condizioni di prova per il campione S3C1 di Roio Piano.

Test No.	σ'_{vc}[kPa]	G_O [MPa]	D (%)
1	100	38	0.69
2	150	49	0.49
3	200	50	0.78
4	250	57	0.48
5	300	63	0.65
6	350	75	0.63
7	400	63	0.60

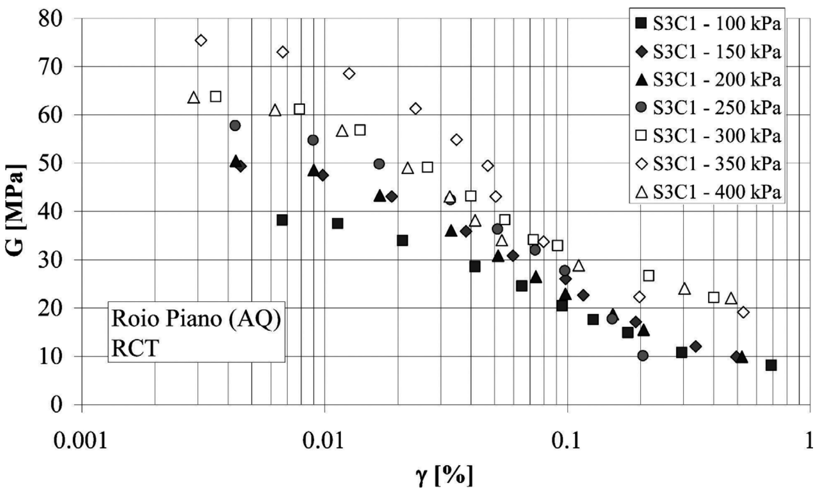


Fig. 12 – G-γ curves from RCT tests.
Fig. 12 – Curve G-γ da prove RCT.

decay with shear strain level were evaluated according to the equation:

$$\frac{G(\gamma)}{G_o} = \frac{1}{1 + \alpha\gamma\,(\%)^{\beta}} \qquad (1)$$

in which:

$G(\gamma)$ = strain dependent shear modulus; γ = shear strain; α, β = soil constants.

The expression (1) allows the shear modulus degradation considered with strain level to be taken into account. The values of α = 15 and β = 1.1 were obtained for Roio Piano sample S3C1. A comparison between the damping ratio values obtained from RCT at different consolidation stresses is shown in figure 14.

The damping ratio values obtained from RCT using the amplitude decade method are very small, ranging between 0.5 % and 1 % for strain levels of less than 0.01 %.

According to many researchers [SHIBUYA *et al.,* 1995; TATSUOKA *et al.,* 1995; LO PRESTI *et al.,* 1996; LO PRESTI *et al.,* 1997a; LO PRESTI *et al.,* 1997b; CAVALLARO, 1997; LO PRESTI *et al.,* 1998] the nature of soil damping in soils can be linked to the following phenomena:

– Non-linearity, which governs the so called hysteretic damping controlled by the current shear strain level. This kind of material damping is absent or negligible at very small strains.
– Viscosity of the soil skeleton (creep) which is relevant at very small strain rates.
– Viscosity of the pore fluid which is relevant at very high frequencies.

Soil damping, at very small strains, is mainly due to the viscosity of the soil skeleton or of the pore fluid, depending on the strain rates or frequencies.

The inverse variation of damping ratio with respect to the normalised shear modulus has an exponential form as reported in figure 13. An interpretation of the experimental results was made, as suggested by YOKOTA *et al.* [1981], according to the equation:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda\,\frac{G(\gamma)}{G_o}\right] \qquad (2)$$

in which:

$D(\gamma)$ = strain dependent damping ratio; γ = shear strain; η, λ = soil constants.

The values of η = 4.18 and λ = 1.921 were obtained for the Roio Piano sample S3C1. The equation (2) assumes maximum value D_{max} = 4.18 % for $G(\gamma)/G_o$ = 0 and minimum value D_{min} = 0.61 % for $G(\gamma)/G_o$ = 1. Therefore, equation (2) can be re-written in the following normalised form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad (3)$$

Finally, figure 16 shows a comparison between the results obtained from resonant column tests performed at the University of Catania on the S3C1sample and the results obtained by other laboratories in the network (Tab. III), for different Roio Piano samples in terms of G/Go -γ curves.

7. Evaluation of G_o from empirical correlations

An attempt to evaluate the small strain shear modulus was also made by means of the following empirical correlations based on penetration test results or laboratory results available in literature.

a) HRYCIW [1990]:

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}}\,\frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w}\,K_o^{\,0.25} \cdot (\sigma'_v/p_a)^{0.5} \qquad (4)$$

where: G_o, σ'_v and p_a are expressed in the same unit; p_a = 1 bar is a reference pressure; γ_D and K_o are respectively the unit weight and the coefficient of

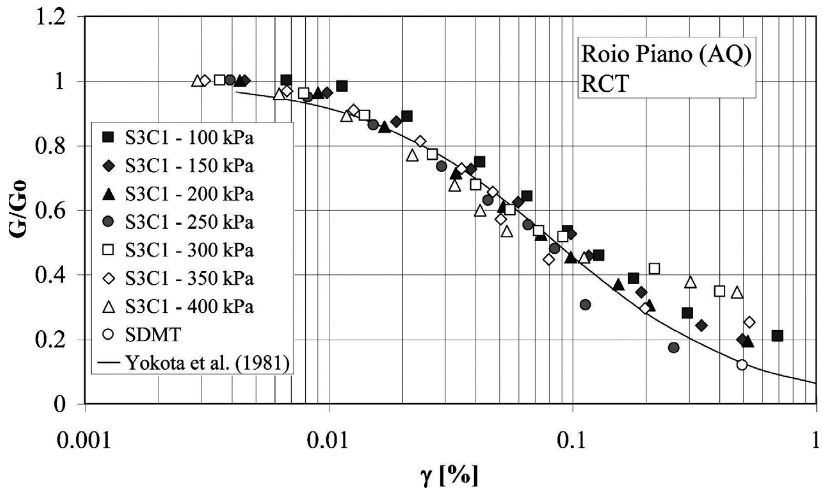


Fig. 13 – G/G_o-γ curves from RCT tests.
Fig. 13 – Curve G/G_o-γ da prove RCT.

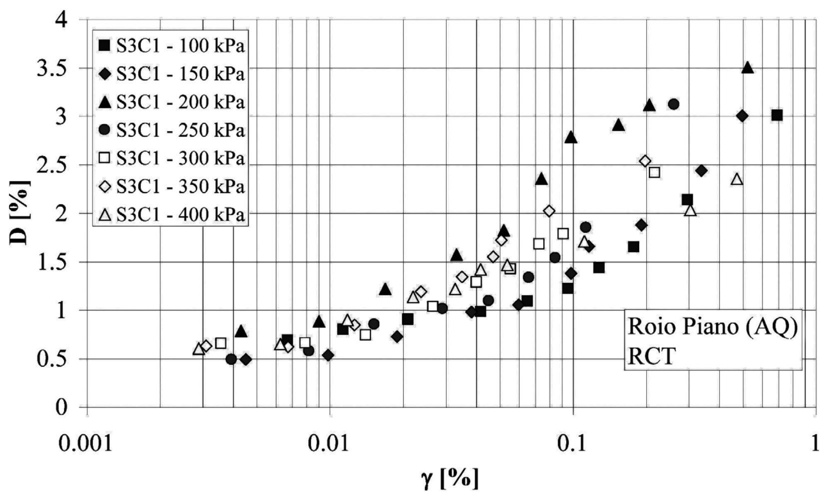


Fig. 14 – Damping ratio from RCT tests.
Fig. 14 – Smorzamento da prove RCT.

Tab. III – Tests carried out in Roio Piano.
Tab. III – Prove effettuate a Roio Piano.

Sample	Depth (m)	Laboratory	Tests
S3 C1	4.00-4.50	Catania	Resonant Column Test.
S3 C2	7.00-7.50	Rome	Double Specimen Direct Simple Shear
S3 C3	12.00-12.50	Florence	Resonant Column Test.
S3 C4	15.00-15.40	Turin	Resonant Column Test.- Torsional Shear Tests
S3 C5	18.00-18.50	Catania	Resonant Column Test.
S3 C7	33.00-33.40	Rome	Double Specimen Direct Simple Shear
S3 C8	49.60-50.00	Naples	Resonant Column Test.- Torsional Shear Tests

earth pressure at rest, as inferred from SDMT results according to MARCHETTI [1980];

b) JAMIOLKOWSKI *et. al.* [1995]:

$$G_o = \frac{530 \cdot \sigma'^{0.5}_m p_a^{0.5}}{e^{1.3}} \qquad (5)$$

where: $\sigma'_m = (\sigma'_v + 2 \cdot \sigma'_h)/3$; p_a = 1 bar is a reference pressure; G_o, σ'_m and p_a are expressed in the same unit. The values for parameters which appear in equation (5) are equal to the average values that result from laboratory tests performed on quaternary

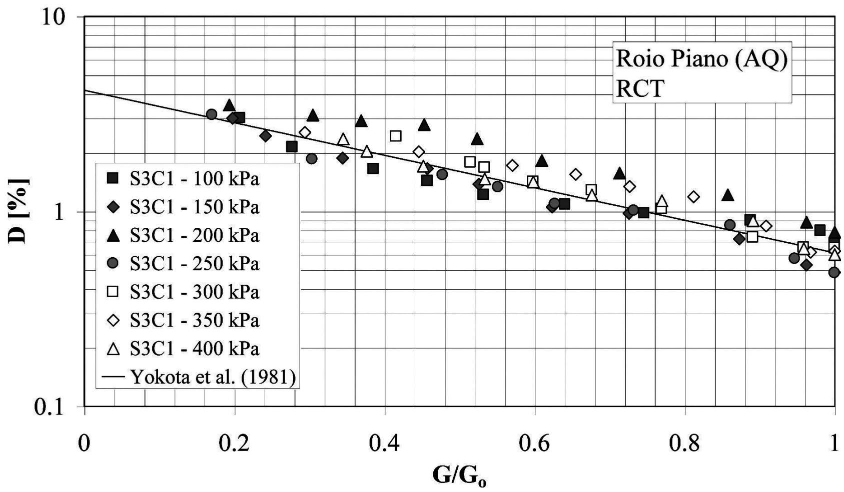


Fig. 15 – D-G/Go curves from RCT tests.
Fig. 15 – Curve D-G/Go da prove RCT.

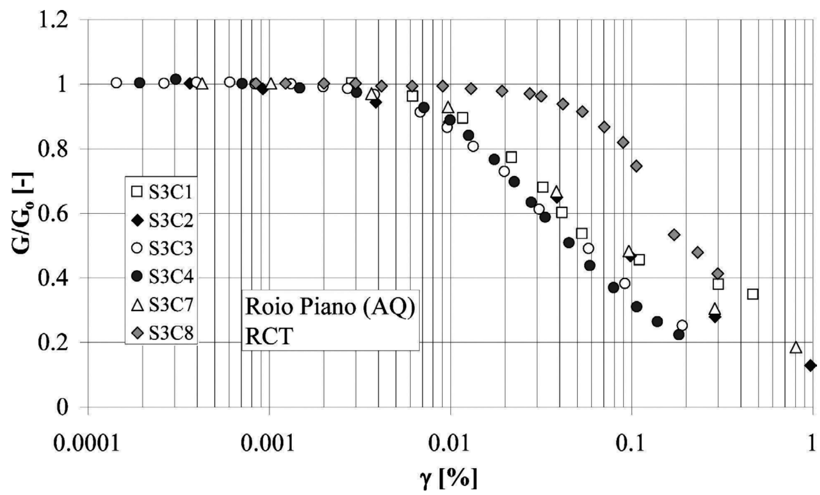


Fig. 16 – G/G_o-γ curves for different Roio Piano samples.
Fig. 16 – Confronto tra le curve G/G_o-γ per differenti campioni di Roio Piano.

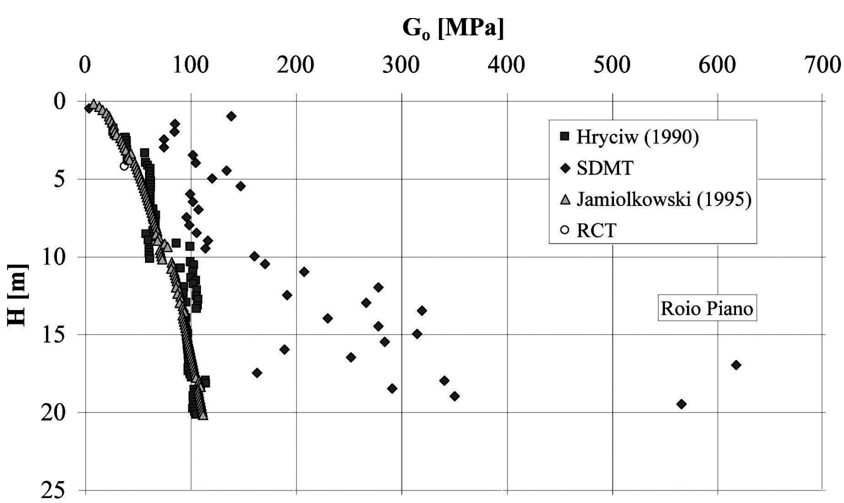


Fig. 17 – G_o from different empirical correlations.
Fig. 17 – G_o per differenti correlazioni empiriche.

Italian clays and reconstituted sands. A similar equation was proposed by SHIBUYA and TANAKA [1996] for Holocene clay deposits.

Equation (5) incorporates a term which expresses the void ratio; the coefficient of earth pressure at rest only appears in equation (4). However only equation (4) tries to obtain all the input data from the SDMT results.

The G_o values obtained with the methods indicated above are plotted against depth in figure 17. The method by JAMIOLKOWSKI *et al.* [1995] was applied considering a given profile of void ratio. The coefficient of earth pressure at rest incorporated by equation (4) was inferred from SDMT.

Equations (4) and (5) give values of G_o in agreement with each other and in agreement with G_o evaluated by RCT. Higher values of G_o were obtained by SDMT. The G_o value obtained by RCT is less than that obtained by SDMT due to soil disturbance during sampling and the cemented soil in situ.

8. Conclusions

The April 6th, 2009 Abruzzo earthquake with a $M_L = 5.8$ and $M_w = 6.3$ struck the city of L'Aquila and the surrounding villages, with a recorded maximum horizontal acceleration of 0.65g at the AQV Station located in the middle of the Aterno Valley; the maximum horizontal and vertical accelerations recorded at the AQK station in the city of L'Aquila were respectively 0.35g and 0.37g. To evaluate soil proprieties static and dynamic laboratory tests were performed, as well as in situ tests, using SDMT apparatus.

As regards the characterization of soil in static field, oedometer tests were performed and the results were compared with the SDMT test results. The OCR values inferred from the oedometer tests are lower than those obtained from the SDMT tests; one possible explanation for these differences could be that the sample was cemented and disturbed.

With regard to the characterization of soil in the dynamic field, the Vs measured by SMDT was in a good agreement with the results given by the D-H and MASW tests. As far as dynamic laboratory tests are concerned, RCT were performed to evaluate shear modulus at small strain (G_o) and the soil non-linearity in terms of decreasing shear modulus G and increasing damping ratio D with shear strain γ. The results agree well with those obtained by the other network laboratories.

Using the RCT test, soil non linearity was evaluated by the normalised curve $G(\gamma)$-logγ(%) and the normalised curve D(%)-G/G_o. The results show that there is a remarkable soil non-linearity which cannot be ignored when site response analysis is performed.

References

AKINCI A., MALAGNINI L., SABETTA F. (2010) – *Characteristics of the Strong Ground Motions from the 6 April 2009 L'Aquila Earthquake, Italy.* Soil Dynamics and Earthquake Engineering, 30, pp. 320-335.

APAT (2006) – *Geological Map of Italy at the Scale 1:50,000.* Sheet No. 359 L'Aquila. S.EL.CA. Firenze.

BERTINI T., BOSI C., GALADINI F. (1989) – *La Conca di Fossa S. Demetrio dei Vestini.* In: CNR, Centro di Studio per la Geologia Tecnica, ENEA, P.A.S.: "Elementi di tettonica pliocenico-quaternaria ed indizi di sismicità olocenica nell'Appennino laziale-abruzzese". Società Geologica Italiana, pp. 26-58.

BLUMETTI A.M. (1995) – *Neotectonic Investigations and Evidence of Paleoseismicity in the Epicentral Area of the January-February 1703, Central Italy, Earthquakes.* In: Serva L. and Slemmons D.B. (Eds.), Bulletin of the Association of Engineering Geologists, Special Publication n. 6 "Perspectives in Paleoseismology", pp. 83-100.

BOSI C., BERTINI T. (1970) – *Geologia della Media Valle dell'Aterno.* Memorie della Società Geologica Italiana, IX, pp. 719-777.

CAVALLARO A.M.F. (1997) – *Influenza della Velocità di Deformazione sul Modulo di Taglio e sullo Smorzamento delle Argille.* Ph. D. Thesis, University of Catania.

CAVALLARO A., LO PRESTI D.C.F., MAUGERI M., PALLARA O. (1999a) – *A Case Study (The Saint Nicolò Cathedral) for Dynamic Characterization of Soil from in Situ and Laboratory Tests.* Proceedings of the 2nd International Symposium on Earthquake Resistant Engineering Structures, Catania, 15 – 17 June 1999, pp. 769-778.

CAVALLARO A., MAUGERI M., LO PRESTI D.C.F., PALLARA O. (1999b) – *Characterising Shear Modulus and Damping from in Situ and Laboratory Tests for the Seismic Area of Catania.* Proceedings of the 2nd International Symposium on Pre-failure Deformation Characteristics of Geomaterials, Torino, 28 – 30 September 1999, pp. 51-58.

CAVALLARO A., MASSIMINO M.R., MAUGERI M. (2003) – *Noto Cathedral: Soil and Foundation Investigation.* Construction and Building Materials, n. 17, pp. 2003, pp. 533-541.

CAVALLARO A., MAUGERI M., Ragusa A. (2004) – *Design Parameters of a Cohesive Soil from Laboratory Tests.* Proceedings of A. W. Skempton Memorial Conference, London, 29-31 March 2004, pp. 381-392.

CAVALLARO A., MAUGERI M. (2005) – *Non Linear Behaviour of Sandy Soil for the City of Catania.* Seismic Prevention of Damage: A Case Study in a Mediterranean City, Wit Press Publishers, M. Maugeri (Ed.), pp. 115-132.

CAVALLARO A., GRASSO S., MAUGERI M. (2006) – *Volcanic Soil Characterisation and Site Response Analysis in the City of Catania.* Proceedings of the 8th National Conference on Earthquake Engineering, San Francisco, 18-22 April 2006, paper n. 1290.

CAVALLARO A., GRASSO S., MAUGERI M. (2007) – *Dynam-*

ic Clay Soils Behaviour by Different in Situ and Laboratory Tests. Solid Mechanics and its Applications, n. 146, 2007, pp. 583-594.

Cavallaro A., Ferraro A., Grasso S., Maugeri M. (2012) – *Topographic Effects of the Monte Po Hill in Catania.* Soil Dynamics and Earthquake Engineering, vol. XLIII, December 2012, pp. 97-113.

Cavallaro A., Cessari L., Gigliarelli E. (2013a) – *Site Characterization by in Situ and Laboratory Tests for the Structural & Architectural Restoration of Saint Nicholas Church, Nicosia, Cyprus.* Proceedings of the 2nd International Symposium on Geotechnical Engineering for the Preservetion of Monuments and Historic Sites, Napoli, 30-31 May 2013, pp. 241-247.

Cavallaro A., Grasso S., Maugeri M., Motta E. (2013b) – *An Innovative Low-Cost SDMT Marine Investigation for the Evaluation of the Liquefaction Potential in the Genova Harbour (Italy).* Proceedings of the 4th International Conference on Geotechnical and Geophysical Site Characterization, ISC'4, Porto de Galinhas, 18-21 September 2012, *Geotechnical and Geophysical Site Characterization 4*, vol. I, 2013, pp. 415-422.

Cavallaro A., Grasso S., Maugeri M., Motta E. (2013c) – *Site Characterisation by in Situ and Laboratory Tests of the Sea Bed in the Genova Harbour (Italy).* Proceedings of the 4th International Conference on Geotechnical and Geophysical Site Characterization, ISC'4, Porto de Galinhas, 18-21 September 2012, *Geotechnical and Geophysical Site Characterization 4*, vol. I, 2013, pp. 637-644.

GNDT-SSN Albarello D., Bosi V., Bramerini F., Lucantoni A., Naso, G., Peruzza L., Rebez A., Sabetta F., Slejko D. (2001) – *New Seismic Hazard Maps of the Italian Territory.* Gruppo Nazionale per la Difesa dai Terremoti – Servizio Sismico Nazionale. (http://www.dstn.it/ssn/PROG/2000/carte_pericolosita/mcs_e.gif).

Grasso S., Laurenzano G., Maugeri M., Priolo E. (2005) – *Seismic Response in Catania by Different Methodologies.* Advances in Earthquake Engineering, 14, pp. 63-79

Gruppo di Lavoro MS–AQ (2010) – *Microzonazione sismica per la ricostruzione dell'area Aquilana. Regione Abruzzo* – Dipartimento della Protezione Civile, L'Aquila, 3 voll. e cd-rom.

Hryciw R.D. (1990) – *Small Strain Shear Modulus of Soil by Dilatometer.* JGED, ASCE, vol. 116, n. 11, pp. 1700-1715.

INGV- *Database Macrosismico Italiano* (2004) – DBMIO4 (http://emidius.mi.ingv.it/DBMI04/).

Jamiolkowski M., Lo Presti D.C.F., Pallara O. (1995) – *Role of In-Situ Testing in Geotechnical earthquake Engineering.* Proceeding of 3rd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamic, State of the Art 7, vol. III, pp. 1523-1546.

Lanzo G., Silvestri F., Costanzo A., D'onofrio A., Martelli L., Pagliaroli A., Sica S., Simonelli A. (2011) – *Site Response Studies and Seismic Microzoning in the Middle Aterno Valley (L'Aquila, Central Italy).* Bulletin of Earthquake Engineering, 9, n. 5, pp.1417-1442.

Lo Presti D.C.F., Jamiolkowski M., Pallara O., Cavallaro A. (1996) – *Rate and Creep Effect on the Stiffness of Soils.* ASCE Convention, Washington, 10-14 Nov. 1996, Geotechnical Special Publication, n. 61, pp. 166-180.

Lo Presti D.C.F., Jamiolkowski M., Pallara O., Cavallaro A., Pedroni S. (1997a) – *Shear Modulus and Damping of Soils.* Proceeding of the International Symposium on the Pre-failure Deformation Behaviour of Geomaterials, 50th Geotechnique, London, 4 September 1997, Géotechnique, 47, n. 3, pp. 603-617.

Lo Presti D.C.F., Pallara O., Cavallaro A. (1997b) – *Damping Ratio of Soils from Laboratory and in Situ Tests.* Proceeding of the 14th International Conference on Soil Mechanics and Foundations Engineering, Hamburg, 6-12 September 1997, Special Volume TC4, pp. 391-400.

Lo Presti D.C.F., Maugeri M., Cavallaro A., Pallara O. (1998) – *Shear Modulus and Damping of a Stiff Clay from in Situ and Laboratory Tests.* Proceeding of the 1st International Conference on Site Characterization, Atlanta, 19-22 April 1998, pp. 1293-1300.

Lo Presti D.C.F., Jamiolkowski M., Cavallaro A., Pallara O. (1999a) – *Anisotropy of Small Strain Stiffness in Undisturbed Clay.* Proceedings of the 2nd International Symposium on "Pre-failure Deformation Characteristics of Geomaterials", Torino, 28-30 September 1999, pp. 3-10.

Lo Presti D.C.F., Jamiolkowski M., Cavallaro A., Pallara O. (1999b) – *Influence of Reconsolidation Techniques and Strain Rate on the Stiffness of Undirsturbed Clays from Triaxial Tests.* Geotechnical Testing Journal, vol. XXII, n. 3, September 1999, pp. 211-225.

Marchetti S. (1980) – *In Situ Tests by Flat Dilatometer.* Journal of the Geotechnical Engineering Division, ASCE, vol. CVI, n. GT3, March, 1980, pp. 299-321.

Marchetti S., Monaco P., Totani G., Marchetti D. (2008) – *In Situ Tests by Seismic Dilatometer (SDMT).* In: "*From Research to Practice in Geotechnical Engineering*", ASCE Geotech. Spec. Publ. n. 180 Honouring John H. Schmertmann, pp. 292-311.

Maugeri M., Simonelli A.L., Ferraro A., Grasso S., Penna A. (2011) – *Recorded Ground Motion and Site Effects Evaluation for the April 6, 2009 L'Aquila Earthquake.* Bull Earthquake Eng., n. 9, pp. 157-179.

Monaco P., Totani G., Barla G., Cavallaro A., Costanzo A., d'Onofrio A., Evangelista L., Foti S., Grasso S., Lanzo G., Madiai C., Maraschini M., Marchetti S., Maugeri M., Pagliaroli A., Pallara O., Penna A., Saccenti A., Santucci de Magistris F., Scasserra G., Silvestri F., Simonelli A.L., Simoni G., Tommasi P., Vannucchi G., Verrucci L. (2012) – *Geotechnical Aspects of the L'Aquila Earthquake.* In: M.A. Sakr and A. Ansal (Eds.) "Special Topics in Earthquake Engineering", Geotechnical, Geological and Earth-

quake Engineering 16, chapter 1, pp. 1-66.
MONACO P., SANTUCCI DE MAGISTRIS F., GRASSO S., MARCHETTI S., MAUGERI M., TOTANI G. (2011) – *Analysis of the Liquefaction Phenomena in the Village of Vittorito (L'Aquila)*. Bulletin of Earthquake Engineering. Special Issue on 2009 L'Aquila Earthquake. Official Publication of the European Association for Earthquake Engineering. Main editor: A. Ansal., vol. IX, n. 1, February 2011, pp. 231-261.
N.T.C. (2008) – *Norme Tecniche per le Costruzioni* (Italian Technical Regulation for Constructions). Decreto del Ministro delle Infrastrutture 14.01.2008, published on Gazzetta Ufficiale 04.02.2008, Roma, 2008.
REBEZ A., SABETTA F., SLEJKO D. (2001) – *New Seismic Hazard Maps of the Italian Territory*. Gruppo Nazionale per la Difesa dai Terremoti – *Servizio Seismico Nazionale*.
SHIBUYA S., MITACHI T., FUKUDA F., DEGOSHI T. (1995) – *Strain Rate Effect on Shear Modulus and Damping of Normally Consolidated Clay*. Geotechnical Testing Journal, 18, n. 3, pp. 365-375.
SHIBUYA S., TANAKA H. (1996). *Estimate of Elastic Shear Modulus in Holocene Soil Deposits*, Soils and Foundations, vol. XXXVI, n. 4, pp. 45-55.
SLEJKO D., PERUZZA L., REBEZ A. (1998) – *Seismic Hazard Maps of Italy*. Annali di Geofisica, n. 41, pp. 183-214.
TATSUOKA F., LO PRESTI D.C.F., KOHATA Y. (1995) – *Deformation Characteristics of Soils and Soft Rocks under Monotonic and Cyclic Loads and Their Relations*. Proceeding of the 3rd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamic, State of the Art 1, n. 2, pp. 851-879.
TERTULLIANI A., ROSSI A., CUCCI L., VECCHI M. (2009) – *L'Aquila (Central Italy) Earthquakes: The Predecessors of the April 6, 2009 Event*. Seismological Research Letters, 80, pp. 1008-1013.
TURINO R. (Ed.) (2010) – *L'Aquila. Il Progetto C.A.S.E.* ASCE. IUSS Press, Pavia.
YOKOTA K., IMAI T., KONNO M. (1981) – *Dynamic Deformation Characteristics of Soils Determined by Laboratory Tests*. OYO Tec. Rep. 3, pp. 13-37.

Caratterizzazione statica e dinamica dei terreni in località Roio Piano (AQ)

Sommario

Dopo il terremoto del 6 aprile 2009 che ha colpito l'Abruzzo, sono state eseguite numerose indagini per la caratterizzazione dei terreni in campo statico e dinamico, con l'obiettivo di analizzare la risposta sismica dei suoli [GRASSO et al.*, 2005; LANZO* et al.*, 2011; MAUGERI* et al.*, 2011], per il recupero o il miglioramento degli edifici e di importanti monumenti storici. Tra le numerose indagini in sito in diverse località della provincia de L'Aquila i risultati delle indagini del sito di Roio Piano sono riportati nel presente lavoro. In particolare, sono riportati i risultati delle prove ottenute con il Dilatometro Sismico di Marchetti (SDMT) e quelli ottenuti con le prove di laboratorio eseguite sul terreno.*

Tra le prove di laboratorio di tipo dinamico, in particolare sono state effettuate prove di colonna risonante per la valutazione dei parametri geotecnici del terreno in termini di modulo G-γ e del rapporto di smorzamento D-γ.